Phosphorus fertilisers, soil tests and off-site water quality

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Introduction

In their natural state, many of the world's soils require phosphorus (P) additions in order to sustain economically viable agricultural production (Connor and Smith, 1987). These phosphorus additions may take the form of organic manures, rock phosphate, or more commonly, manufactured fertilisers. The manufacturing process generally increases the nutrient content of the fertiliser, thereby reducing transport and application costs, and increases the solubility of the phosphorus, and hence its immediate availability to plants. Worldwide, approximately 15 million tonnes of fertilisers, representing 40% of the global phosphorus budget, are applied to land annually (Sheldrick et al., 2003).

In recent years there has been increasing concern over production and use of phosphorus fertilisers. These concerns range from industrial pollution during fertiliser manufacture, including the production of phosphogypsum, a by-product of wet process phosphoric acid production that contains natural radionuclides such as radium (Rutherford et al., 1994; Scholten and Timmermans, 1996) and the off-site impacts of the nutrients and other fertiliser constituents on aquatic ecosystems. This paper will investigate fertiliser use and its relationship to water quality in agricultural catchments. Using that background, key questions relating to the causes of water quality problems will be discussed, including the possible use of agronomic soil tests for estimating the risks of phosphorus being exported from particular land uses.

Key questions associated with the environmental impacts of fertiliser use

How can fertiliser use adversely affect off-site water quality?

The application of phosphorus fertilisers in agricultural catchments can adversely affect off-site water quality in a number of ways. Fertilisers contain trace metal contaminants. Recent studies have shown that while the concentrations of the various metal species in surface drainage from irrigated pastures were within the guidelines for potable water, concentrations of copper, zinc, cadmium, lead and nickel were above the trigger levels for freshwater systems (i.e. where investigation of the effects is warranted) (Nash et al., 2003a). As metal concentrations increased after fertiliser application, it seems likely that these concentrations are attributable to anthropogenic sources and that metal contamination of freshwater will become increasingly important, especially if soil and stream water acidification increase metal availability.

By far the most important environmental issue associated with the use of phosphorus fertilisers is the export of small quantities of phosphorus, often less than 5% of that applied (Nash and Murdoch, 1997; Nash, 2002), into surface waters and, to a lesser extent, ground waters. Plants extract nutrients from the soil water. It follows that in making nutrients available to plants they are made available to water, and the export of nutrients, such as
phosphorus, is a natural consequence of plant production. It also follows that all else being equal, increasing soil fertility increases the potential for phosphorus exports.

Where are phosphorus fertilisers applied and how does that relate to water quality?

The Australian National Land and Water Audit (2001) illustrated, not unexpectedly, that phosphorus applications (>10 kg P/ha) and soil test phosphorus values are generally higher in high rainfall regions particularly, the dairy/intensive livestock and horticultural areas of Victoria and Tasmania (Figure 1). The study showed soil test phosphorus was increasing (i.e. positive phosphorus balance) fastest in the dairying and horticultural regions of southern and northern Victoria, Tasmania and South Australia, higher rainfall areas of WA and some restricted areas in northern Queensland. Interestingly, in areas of south-eastern Queensland, the Riverina, northern Regions of NSW, southern Wimmera and north-eastern Victoria, soil phosphorus was being mined (i.e. negative phosphorus balances).

Figure 1. Distribution of topsoil phosphorus determined by commercial soil testing (1989-1999)

(National Land and Water Resources Audit, 2001)

The areas of Australia with high fertiliser use and soil test phosphorus values coincide with the areas where nutrients are a major surface water quality issue (Figure 2). These areas include most of the more intensively developed basins along the north-east coast, Murray-Darling Basin, south-east coast and south-west coast.
Australia's agricultural industries, sewage treatment plants, urban areas and manufacturing industries all contribute to the phosphorus in our water supplies. The relative importance of different nutrient sources appears to vary from catchment to catchment. However, there is little doubt that at a catchment scale, increasing soil fertility as a result of agricultural development has increased the transfer of phosphorus from land to water and consequently deteriorating water quality is a feature of some key Australian catchments (Figure 2).

Figure 2. Surface water total phosphorus in excess of guidelines (2000)
How much phosphorus is too much?

The phosphorus concentration that would result in natural waters being classed as degraded is relatively small compared with the amount of phosphorus used in grazing systems. Water is considered degraded or poor if the total phosphorus concentration exceeds 0.050 mg/L (Cottingham et al., 1995) or about 75 g or 35 cm$^3$ (i.e. a matchbox full) of phosphorus in an Olympic sized swimming pool. In comparison the total phosphorus concentration in the soil water can exceed 1 mg/L on many farms (Sanyal and DeDatta, 1991; Slattery et al., 1998; Toifi et al., 2000)

How costly are the water quality problems associated with phosphorus exports?

It is often difficult to quantify the costs of phosphorus exported from agricultural land. In itself, phosphorus is rarely harmful to receiving waters. In aquatic systems, as in terrestrial systems, phosphorus stimulates plant growth and it is through that mechanism that the adverse effects of additional phosphorus in water are expressed. For example, fertiliser phosphorus no doubt contributed to the 1991 blue-green algal bloom in the Darling-Barwon system that extended over 1000km and cost $1.3B AUS (Department of Water Resources, 1992). The role of phosphorus from non-agricultural sources, phosphorus mobilised from the river sediments and other factors such as temperature and light in stimulating the bloom are arguable (Grace et al., 1997). However, what is clear, is that phosphorus can be a limiting nutrient in many inland waters (i.e. limits biomass production) and therefore decreasing phosphorus exports from agricultural land is desirable (Weaver et al., 1994; Government of Victoria, 1995).

Why do we use phosphorus fertilisers and how efficient are they?

Phosphorus is an important nutrient affecting the ecological balance of aquatic and terrestrial habitats. In terrestrial ecosystems, increased soil phosphorus fertility is often desirable. It favours the single species dominance required by many agricultural systems. Unfortunately, it can also make it difficult to regenerate species rich communities and increase biodiversity (Willems and Van Nieuwstadt, 1996; Janssens et al., 1998).

Compared to other major plant nutrients phosphorus is poorly utilised by crops. The sorption of phosphorus by soils and the slow mobilisation of orthophosphate ions into solution reduce the effectiveness of fertiliser applications (Holford, 1997). For these reasons phosphorus fertilisers are generally used to raise soil test phosphorus above a “critical” value for optimum production and meet the short-term phosphorus needs for particular stages of plant growth (i.e. starter applications). It follows that fertiliser efficiency, calculated as the difference in phosphorus uptake with and without fertiliser, declines with increasing soil fertility and is often less than 10% on soils well supplied with phosphorus (McKenzie et al., 2003). However, because soils fix phosphorus in forms that are unavailable to crops, even fertile soils require phosphorus additions to maintain their productive capacity (Burkitt et al., 2002b).
What do agronomic soil tests measure and how do they relate to fertiliser use?

Agronomic soil tests (i.e. 0-10 cm) are generally distinguished on the basis of whether they measure the “quantity” or “intensity” of phosphorus in soil. The “quantity” is commonly that portion of soil phosphorus that is potentially available uptake during the crop cycle. “Intensity” is the phosphorus concentration (activity) in soil solution (Moody and Bolland, 1999). Unfortunately soil phosphorus tests are not a precise instruments, and the critical soil test phosphorus value for a particular crop depends on the growing conditions and a range of soil properties (Burkitt et al., 2001; Burkitt et al., 2002a; Burkitt et al., 2002b). As a result, many land managers choose to apply phosphorus fertiliser as “insurance” against sub-optimal production, especially for high value enterprises. The proportion of Australian soils having high and in some cases excessive soil test phosphorus values demonstrates this.

How is phosphorus exported from agricultural systems?

Phosphorus is exported from agricultural systems when there is (1) a source of phosphorus that is (2) mobilised into water and (3) transported to a point where its (4) adverse effects are expressed. In Australia mobilisation is a crucial step that is often overlooked in assessing the potential for water quality impairment. Phosphorus, can be mobilised either in association with soil particles (>0.45 µm) or by dissolution in water (<0.45 µm or about the size of viruses or smaller). The detachment and transport of sediments, often called erosion, is essentially a physical process that requires kinetic energy for sediment detachment (i.e. raindrop energy) and transport (i.e. flowing water). The selective transport of fine material can increase the concentration of phosphorus in the sediment above that in the soil from which it was derived (Menzel, 1980; Sharpley, 1980, 1985b). Dissolution on the other hand, is largely a chemical process that is affected by the chemistry of phosphorus and the surrounding materials, and the time available for reactions to take place.

Water movement over and through soil are the main pathways by which contaminants, such as phosphorus, are transported off-site. The pathways are rarely as well defined as Figure 3 suggests. Due to their physical size, detached (eroded) sediments (>0.45 µm) rarely move downward except in very sandy soils.

Sub-surface pathways include water moving just below the soil surface (interflow); water moving slowly through the soil fabric (matrix flow); and/or water moving quickly through large soil pores (macro-pore or by-pass flow) (Kirkby et al., 1997). As contaminants move through the soil, some attach to the soil fabric and are removed from the water. This commonly occurs with phosphorus and the concentration decline during sub-surface transport depends primarily on the time that the water and soil are in contact, and soil chemical properties, such as the phosphorus sorption capacity (Nash and Halliwell, 1999). There is little change in phosphorus concentrations where water moves quickly through large soil pores (macro-pore flow) to a porous region of the profile from where it is conveyed laterally to a stream. Artificial sub-surface drainage can readily perform this later function (Armstrong and Harris, 1996; Dils and Heathwaite, 1996) and can increase contaminant exports, particularly in horticultural areas.

Surface runoff (overland flow) facilitates surface transport of contaminants, especially those such as phosphorus that would otherwise attach to the soil fabric. Surface runoff is generally caused by excessive water additions that the soil could not take in within the required period (infiltration excess overland flow) and/or sub-surface flow that has re-emerged at the surface (saturation excess overland flow).
If land management is the problem why don’t farmers do something about it?

In the areas most at risk (i.e. high soil test phosphorus and high rainfall/irrigation areas), it would appear that the majority of the phosphorus used by crops or pastures is probably supplied from fertilisers that have been applied some years earlier, rather than directly from
recently applied fertilisers. It follows that most of the phosphorus exported from these systems is already stored in the soil and therefore not under the immediate control of the land manager. The term "systematic" has been used to define phosphorus exports that are not under the control of the land manager. However, there are land management activities, such as fertiliser application, manure spreading, cultivation and overgrazing that increase phosphorus exports above what would otherwise have occurred. By definition, phosphorus exports resulting from these activities are "preventable" (Nash, 2002).

The "systematic" and "preventable" components of phosphorus exports from south-eastern Victorian dairy pastures have been quantified (Nash et al., 2000; Nash, 2002). These studies showed that the major variables affecting phosphorus exports were the year (i.e. the "systematic" component) followed by the timing of fertiliser and grazing in relation to when surface runoff occurred (i.e. the "preventable" component). Importantly, if the results of these studies were applied to the catchment, it would appear that less than 10% of the phosphorus exports from rainfed farms with similarly fertile soils (Olsen P 30–60 mgP/kg) would be under management control in the short term (i.e. <5 yrs) (Nash, 2002). Assuming reasonable management, the most important factor affecting phosphorus exports from these farms was the ability of the soil/plant system (i.e. the phosphorus source) to mobilise phosphorus at the time of runoff. Interestingly, in these studies soil test phosphorus (Olsen P, 0-10 cm) was not related to the systematic phosphorus component, probably due to changes in surface soil (0-2 cm) phosphorus. It would appear that with current land use there are limited options for decreasing phosphorus exports in the short term.

Is there an obvious environmental target for agronomic soil tests?

There has been a huge investment in developing tests for soil fertility and calibrating them to yield (Gourley, 1987; Edmeades, 2003). Target soil test phosphorus values for optimum production have been developed for most production systems (Peverill et al., 1999). While there are a number of proprietary systems for developing soil and fertiliser recommendations, it is reasonable to assume that most recommend similar targets. Environmental soil test phosphorus targets, especially those used in Australia, have received less study (Sims, 1993; Sharpley et al., 1996; Sims, 1998a; Sims, 1998b, 2000; Sims et al., 2000; Sims et al., 2002).

A number of studies purport to have developed relationships between soil test phosphorus and dissolved phosphorus concentrations in drainage (Maguire and Sims, 2002b, a). Studies of sub-surface pathways in particular appear to indicate that there may be a critical value, termed the "change point", above which phosphorus concentrations increase dramatically. For example, the original of these studies, a field investigation in England (Johnston, 1969), found a strong relationship between Olsen P (0-10 cm) and the phosphorus in drainage from a single soil type. A change point was noted at Olsen P 57 mg P/kg (Heckrath et al., 1995). Later studies using model systems have measured "change points" as low as 10 mg P/kg Olsen P (Hesketh and Brookes, 2000). However, most studies have found that the agronomic target was less than the change point (environmental target) (Sibbesen and Sharpley, 1997).

The notion of a change point that is soil type specific is appealing from a regulatory point of view. However, it is more likely the point of inflection noted in these studies reflects the change between low- and high-energy adsorption sites (Barrow, 1983; Holford, 1997) to which a continuous curve would provide an equally, if not more, robust model for many soils. Further, in the absence of significant macropore flow, the soil properties below the layer in which soil test phosphorus was measured are likely to have more effect on phosphorus exports than the soil test phosphorus itself.
What are the deficiencies of using agronomic soil tests to estimate phosphorus export potential?

Agronomic soil tests were designed to relate soil fertility to plant growth/yield. The two most common soil phosphorus tests in Australia, the Olsen and Colwell P tests, both use bicarbonate solutions (0.5 M NaHCO₃ at pH 8.5) to extract phosphorus. The shorter duration (30 min.) Olsen P test measures both phosphorus quantity (i.e. supply) and intensity (i.e. concentration) while the Colwell P (16 hr.) predominantly measures phosphorus quantity (Moody and Bolland, 1999). As phosphorus mobilisation is both a function of the phosphorus concentration in solution and ability to resupply that phosphorus, neither test would be expected to reliably predict the short-term (i.e. <48 hr.) mobilisation of dissolved phosphorus by water. This is especially true where the phosphorus concentration is independent of flow, suggesting that phosphorus dissolution is rate, rather than supply limited (Nash et al., 2000; Haygarth et al., 2004). Other tests, such as water soluble phosphorus, dilute (0.01M) Calcium Chloride P and iron strip P, have been developed in order to predict phosphorus dissolution potential (Maguire and Sims, 2002b).

If we use an environmental soil test phosphorus target will the way we sample the soil matter?

A major deficiency in using agronomic soil tests to infer environmental impacts, especially in pasture and no-till cropping systems, is the soil sampling depth. It is generally accepted that most mobilisation of phosphorus occurs in the top ca. 0-2 cm of soil (Sharpley, 1985a). Agronomic tests measure the root zone (i.e. 0-10 or 0-15 cm) or deeper. Where phosphorus has accumulated at the soil surface, the increased depth of sampling underestimates soil test phosphorus at the surface where the initial interaction between the water and soil/plant systems occurs. It follows that an Olsen P of 60 where phosphorus is well distributed through the root zone has less potential for phosphorus mobilisation than the same soil with the same soil test phosphorus value but the bulk of the phosphorus in the surface 2 cm. This has implications for management. It broadly suggests that intensively managed pastures that undergo a regular renovation cycle that includes cultivation, may have a higher soil test phosphorus value and lower environmental impact than a lower input system where phosphorus accumulates at the surface (0-2 cm) year after year. Additional factors that may adversely affect the ability of agronomic soil tests to accurately reflect dissolved phosphorus export potential include the exclusion of some plant material and other organic matter during sample preparation (Jones and Bromfield, 1969; Bromfield and Jones, 1972; Singh and Jones, 1976; Sharpley, 1981; Fox et al., 1990b, a; Iyamuremye and Dick, 1996).

Where phosphorus is mobilised into water by physical processes, agronomic soil test phosphorus values are similarly limited. While generally related to the total phosphorus in soil, agronomic soil tests do not consider the size distribution of phosphorus fractions or their bio-availability in receiving waters. The preferential transport of light sediments that are richer in phosphorus increases phosphorus exports and relates more to soil physical, rather than chemical properties.

Is there no role for agronomic soil phosphorus tests in helping decrease exports from agricultural systems?

Despite being a blunt instrument, agronomic soil tests provide the cheapest, and often the only estimate of phosphorus accumulation and phosphorus export potential in agricultural
soils. There can be little argument that where soils are clearly above the soil test phosphorus target for optimum production a nutrient reduction strategy and management to decrease phosphorus exports is warranted. This suggests that an upper limit on soil test phosphorus values for various productions systems may be of merit. In deciding the numerical value of such a cap, soil and plant properties would need to be considered along with the variation in tests values due to sampling procedures, the time of sampling and the differences between laboratories. Consequently, the soil test phosphorus cap would need to be well above the agronomic target for the optimum plant production.

Apart from a lack of precision are there other risks associated with using agronomic soil testing to identify agricultural systems that are susceptible to excessive phosphorus exports?

The risk of using an environmental cap or target based on agronomic soil testing is that we bias our thinking towards low input, less productive systems. These systems are less productive because they have lower soil test phosphorus values. They don't necessarily have lower phosphorus export potential.

Does higher soil fertility as measured by soil test phosphorus mean greater environmental impact?

Consider the following example. Farm A has an Olsen P of 12 mg P/kg (0-10 cm), produces 4500L of milk (3000 L/cow and SR 1.5 cows/ha) and exports 4.0 kg P/ha annually. Farm B has an Olsen P of 35 mg P/kg, produces 12500 L (5000 L/cow and SR 2.5 cows/ha) of milk and exports 5.2 kg P/ha annually by preventing phosphorus exports directly from fertilisers and phosphorus accumulation at the soil surface. Which farm has the bigger environmental impact? Which farm is the more sustainable? And which farm is more environmentally productive? To some extent the answers to these questions are counter intuitive and challenge fundamental notions about how we measure environmental impact.

It could be argued that Farm B has less impact per unit of production than Farm A (0.4 versus 0.9 g/L milk) and is therefore more environmentally productive. That being the case, there are clear economic and environmental arguments for retiring marginal land and concentrating/intensifying production in the most appropriate areas in our catchments. Perhaps in the future we will see “environmental structural adjustment” programs.

If fertiliser application is one of the few tools available to the land manager to decrease exports, can we apply fertiliser without exporting excessive phosphorus?

Fertilisers and good water quality are not mutually exclusive. Research has shown that fertilisers can be used effectively without unacceptable environmental impacts (Nash, 2002). Deep placement, banding and increasing the time between fertiliser application and runoff can contribute to achieving this objective (Timmons et al., 1973; Janssen et al., 1999; Kimmell et al., 2001).

Fertiliser selection based on the properties of the system in which it is to be used can also lessen phosphorus exports. For example, fertilisers vary in their solubility (Chien et al., 1989; Nash et al., 2003b) On sandy soils, the use of slowly soluble phosphorus sources decreases phosphorus exports through sub-surface pathways (Weaver et al., 1988a; Weaver et al.,
For border-check irrigation where phosphorus is exported in surface runoff, rapidly soluble fertilisers such as Di-ammonium Phosphate (DAP) infiltrate at the wetting front, decreasing phosphorus exports (Nash et al., 2004). In rainfed systems, the most appropriate fertiliser depends on the hydraulic properties of the soil when runoff is induced. Again, somewhat counter intuitively, slow release fertilisers are not necessarily the most environmentally friendly.

**Concluding comments**

In making nutrients available to plants we make nutrients available to water. Nutrient exports are a natural consequence of plant production. As an approximation, the increased soil fertility and nutrient cycling required by productive agricultural systems increases nutrient exports compared to pristine systems. Fertilisers in whatever form, past, present and future are part of productive agriculture and increase phosphorus exports. But, unproductive agriculture is not necessarily low impact agriculture.

As fertility improves so does productivity and the proportion of exported phosphorus derived from recently applied fertilisers diminishes. It follows that phosphorus exports from Australia’s most productive soils and productive farming systems are largely not under the control of the land manager and remedial strategies based on phosphorus input and output management (budget approaches), will take years, if not decades, before they have a measurable impact on catchment water quality.

Agronomic soil tests, such as Colwell P and Olsen P, were designed to estimate the soil fertility and are used as a basis for fertiliser recommendations. Amongst progressive farmers, in Australia, as in western Europe, the use of soil sampling and the application of technologies that match fertiliser applications to soil nutrient status and yield potential, are becoming more widespread (Oliver and Frogbrook, 1998; Juang et al., 2002). However, in Europe at least, it is still unclear whether greater precision is economically justified (Vanoverstraeten and Hanotiaux, 1996; Edwards et al., 1997; Sylvester-Bradley et al., 1999; Neyroud and Lischer, 2003). Agronomic soil tests are not necessarily a precise instrument. They do not measure the attributes of soils, such as phosphorus accumulation at the soil surface, water extractable phosphorus in living and decaying organic matter and organic matter interference with phosphorus adsorption, that affect phosphorus mobilisation prior to its transport off-site.

Plant production systems leak phosphorus. Optimising production systems to decrease phosphorus exports (i.e. leakage) is a realistic option. However, in making these changes we need to use our head and not our hearts as many of the changes that are needed are counter intuitive and probably mean intensifying production in some areas and retiring land in others. The notion of an environmental soil test phosphorus target is appealing and potentially useful if its deficiencies are acknowledged. It is a tool that at a policy (i.e. catchment) level can indicate where potential problems associated with excessive phosphorus exports are likely to arise. But it is a tool that can be biased against productive agriculture. There is no question that some soils have been excessively fertilised and their fertility, as measured by agronomic soil test phosphorus values, should be lowered. But if we are going to aim at a target somewhere in the distance, let’s not pretend we are using a sniper’s rifle when we are really using a demolition ball swinging freely from a gantry!
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